Effects of Ag buffer layer on the magnetic properties of ultrathin Co/Ge(111) films

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The influences of an Ag buffer layer on the magnetic properties of ultrathin Co/Ge(111) films grown at ambient temperature were studied using the surface magneto-optic Kerr effect technique. Due to the intermixing of Co adatoms and Ge(111) substrate, a nonferromagnetic layer forms at the initial stage of the deposition for Co/Ge(111) films. We demonstrate experimentally that the ferromagnetic inactive layer can be reduced by introducing an Ag buffer layer and the orientation of the easy axis of magnetization remains unchanged. Three magnetic phases have been resolved for Co/Ag/Ge(111) films with a Ag thickness less than 6 monolayers. In the phase diagram, the boundary between ferromagnetic and nonmagnetic regions shifts to a lower Co thickness from 10 to 5 monolayers as the thickness of the Ag layer increases from 0 to 6 monolayers. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1540134]

I. INTRODUCTION

Investigations of metal/semiconductor interfaces are of continuing scientific and technological interest.[1–11] Within this broad field, the studies of nanometer-scale magnetism have a special place since the current standard of electronic devices and data storage media has reached a level such that magnetic materials have to be fabricated on a nanometer scale. The emerging concept of spintronics requires the assembling of nanometer-sized magnetic structures with desired magnetic properties. This background motivates scientists and engineers to attempt to grow and characterize magnetic objects at smaller length scales. As a basic element of magnetic structures, magnetic films have been investigated extensively in the past decades. Magnetic properties of a magnetic film are usually modified by the addition of an interface and the modification of the physical properties is more pronounced as the film thickness approaches the ultrathin limit.[12,13] This provides an opportunity for the detailed understanding of magnetic structures. In this article, we have reported on the effects of a Ag buffer layer on the magnetic properties of ultrathin Co/Ge(111) films using the *in situ* surface magneto-optic Kerr effect (SMOKE) technique.

The formation of Co–Ge compounds at the interface of a Co/Ge film has been verified by photoemission spectroscopic measurements for the room temperature deposition of cobalt on a Ge surface.[5,6] The CoGe compound layers are nonferromagnetic.[7] Since Ag and Co are immiscible in the bulk phase diagram up to 600 °C,[14] we chose Ag as a buffer layer between the Co overlayer and the underlying Ge(111) substrate. The Ag/Ge(111) system follows the Stranski–Krastanov growth mode with the Ag island growing epitaxially on an intermediate structured layer.[8] The segregation of a small amount of Ge on the growing Ag overlayer has been identified during the deposition of Ag film on a Ge(111) surface by photoemission spectroscopy.[9] As cobalt is deposited on a Ge(111) substrate at 300 K, a low-energy electron diffraction (LEED) measurement reveals a 1×1 structure of the system up to 5 monolayers (ML).[10]

II. INSTRUMENTATION

Experiments were conducted in an ultrahigh vacuum (UHV) chamber with a background pressure of about 2×10^{-10} Torr. The UHV chamber was equipped with instruments for SMOKE, LEED, Auger electron spectroscopy (AES), and x-ray photoemission spectroscopy (XPS) measurements. The various components are described in detail elsewhere.[2,3] The Ge(111) surface was cleaned with cycles of Ar^+ ion bombardment and annealing treatments. The samples were cooled with a slow rate of 2 K/min after the annealing treatment at 1100 K. A well-ordered $c(2\times8)$ LEED pattern of the Ge(111) surface was observed after this procedure as reported before.[4,11] The surface of the Ge crystal was cleaned after each experiment when working with cobalt overlayers. The coverage of the cobalt overlayer was determined from the ratio of the intensities for Co and Ge

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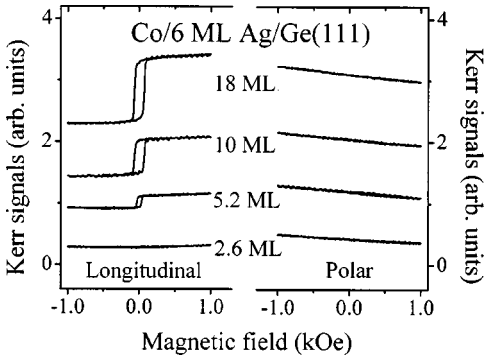

FIG. 1. Thickness dependencies of the hysteresis loops for *x* ML Co/6 ML Ag/Ge(111) films on both the longitudinal and polar configurations. No hysteresis occurs on the polar configuration. The easy axis of magnetization of the films is in the surface plane.

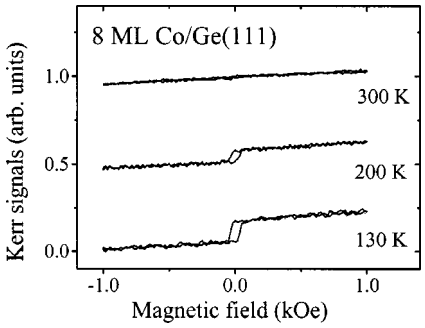

FIG. 3. Kerr signals vs the magnetic field for 8 ML Co/Ge(111) on the longitudinal configuration. There is no hysteresis for the film deposited and measured at 300 K. After cooling the sample down to 200 K, hysteresis occurs.

Auger signals and was double checked by a SYCON thickness monitor of a quartz balance. One ML of cobalt is equal to 0.8 Å ($=7.2\times10^{14}$ atoms/cm^2) for Co growing on a Ge (111) surface.

III. RESULTS AND DISCUSSION

Figure 1 shows the Kerr signals versus magnetic field for ultrathin Co/6 ML Ag/Ge(111) films grown at an ambient temperature. At the initial stage of the Co growth on the surface of 6 ML Ag/Ge(111), no hysteresis occurs below 2.6 ML of Co thickness. The films are nonferromagnetic. Ferromagnetism occurs while the thickness of the Co films increases to above 5.2 ML as revealed by the occurrence of the hysteresis loops on the longitudinal configuration. No magnetic hysteresis observable on the polar configuration shows that the easy axis of the magnetization for Co/Ag/Ge(111) films is in the surface plane with Co thickness up to 26 ML.

Thickness dependencies of the remanent Kerr intensities for both the ultrathin Co/Ge(111) and Co/6 ML Ag/Ge(111) films are shown in Fig. 2 as a comparison. After the deposition of ultrathin Co films on a Ge(111) surface, the longitudinal Kerr intensity is zero up to 8 ML. Subsequent Co deposition causes a linear increase of the longitudinal Kerr intensity at the Co thickness above 10 ML. As a result of our observation of the linear increase of the Kerr intensity, one can conclude that the Curie temperatures of Co/Ge(111) films in this thickness range are well above the measurement temperature. This is consistent with the increase of the Curie temperature upon thickness increasing for ultrathin magnetic films.[15] Straight-line extrapolation of the data to a zero signal as indicated by a dashed line shows an intercept about 3.8 ML. This represents that the first-four-ML Co intermixes with the Ge(111) substrate to form a nonferromagnetic CoGe compound irreversibly. Co films with thickness between 3.8 to 8 ML exhibit a nonferromagnetic behavior because the Curie temperatures are below the measurement temperature of 300 K. As an example, Fig. 3 shows the temperature dependence data for 8 ML Co/Ge(111) from 300 to 130 K. The as-deposited film shows no hysteresis. After cooling the sample with a temperature step of 25 K, hysteresis loops were observed at temperatures lower than 200 K. This means that the Curie temperature of the film is about 200 K. After inserting 6 ML Ag as a buffer layer between the Co layer and the Ge(111) substrate, there is also no hysteresis on the polar configuration. Easy axis of magnetization remains on the surface plane. After checking the plot of the longitudinal Kerr intensity versus the Co thickness as shown in Fig. 2, one can find that the evolution of the Kerr intensity is similar to that without a buffer in Co/Ge(111) film besides the thickness of the nonferromagnetic layers is efficiently reduced to zero. Ag and Co are immiscible up to 600 °C as shown in their bulk phase diagram.[14] Even segregation of a small amount of Ge on a Ag/Ge(111) system has been reported,[9] Co films (or a Co-rich layer) which show no ferromagnetic-dead layer are observed for predeposition of 6 ML Ag on the Ge(111) substrate.

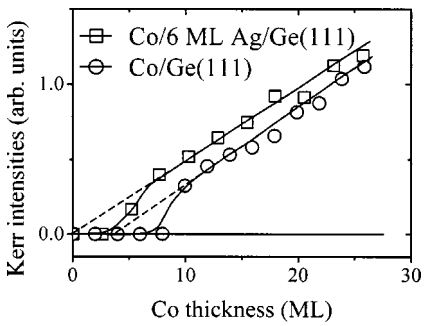

FIG. 2. Thickness dependencies of the remanent Kerr intensities for ultrathin Co/6 ML Ag/Ge(111) (squares) and Co/Ge(111) (circles) films grown at 300 K on the longitudinal configuration. The nonferromagnetic layer is efficiently reduced to zero by using 6 ML Ag as a buffer layer.

A magnetic phase diagram deduced from these arguments is summarized in Fig. 4 for Co/Ag/Ge(111) films with Ag coverage less than 6 ML. Three regions have been resolved in the phase diagram. In regions I and II, the films are nonferromagnetic. From the analysis of a magnetic-dead layer in Fig. 2, the nonferromagnetic Co film in region I is attributed to the formation of a nonferromagnetic Co–Ge compound. In region II, Co films (or a Co-rich layer) are nonferromagnetic because the Curie temperatures are below the measurement temperature of 300 K. These layers merge into the subsequently deposited Co and reveal ferromagnetism as the thickness of the Co films becomes large enough. In region III, Co films are ferromagnetic with an

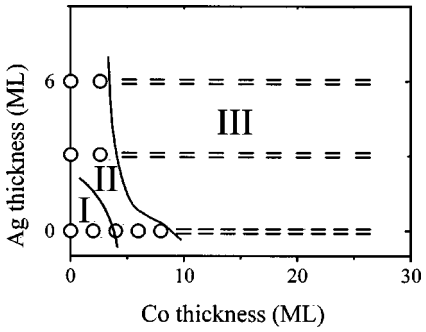

FIG. 4. Magnetic phase diagram of binary-metal Co/Ag on a Ge(111) surface at 300 K. The phase diagram can be divided into three regions. In regions I and II represented by circles, the disappearance of magnetic hysteresis suggests that the films are nonferromagnetic. In region III represented by horizontal lines, the films exhibit an in-plane anisotropy.

in-plane anisotropy. The Ag buffer layer does not influence the anisotropy of the Co/Ge system.

In summary, the ferromagnetic inactive layers at the Co/Ge interface are formed due to the intermixing of Co and Ge. We demonstrate that the ferromagnetic inactive layers can be reduced by introducing a Ag buffer layer without changing the magnetic anisotropy. After summarizing the magnetic phases for Co/Ge(111) and Co/Ag/Ge(111) films, three regions were resolved: (I) nonferromagnetic Co–Ge compound layer, (II) nonferromagnetic Co phase with the Curie temperatures below 300 K, and (III) magnetic phase with an in-plane anisotropy. The boundary between ferromagnetic and nonferromagnetic regions shifts to a lower Co thickness from 10 to 5 ML as the thickness of the Ag layer increases from 0 to 6 ML.

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